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Failure of Standard Optical Models to Reproduce Neutron Total Cross Section Differences in the W Isotopes

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Recently cross section differences among the isotopes ^{182,184,186}W have been measured as part of a study of total cross sections in the 5–560 MeV energy range.[1)] These measurements show oscillations up to 150 mb between 5 and 100 MeV. Spherical and deformed phenomenological optical potentials with typical radial and isospin dependences show very small oscillations, in disagreement with the data. In a simple Ramsauer model,[2–4)] this discrepancy can be traced to a cancellation between radial and isospin effects. Understanding this problem requires a more detailed model that incorporates a realistic description of the neutron and proton density distributions. This has been done with results of Hartree-Fock-Bogolyubov calculations using the Gogny force, together with a microscopic folding model employing a modification[5,6)] of the JLM potential as an effective interaction. This treatment yields a satisfactory interpretation of the observed total cross section differences.

KEYWORDS: neutron total cross sections, Ramsauer model, spherical optical model, coupled–channels optical model, microscopic folding models

I. Introduction

Differences of neutron total cross sections among neighboring nuclei provide unusually stringent tests of optical models. In many cases standard optical potentials with nuclear radii proportional to $A^{1/3}$ and with typical strengths for isovector components (U_1/U_0 approximately 0.5 in the usual expression $U = U_0 \pm U_1(N-Z)/A$) have yielded reasonably good agreement with measured cross section differences. Examples may be found in the Ce region[7)] and in the Nd–Sm region,[8)] as well as ^{238}U–^{232}Th.[9)] The results in the Ce region have also been reproduced with a microscopic folding model.[10)]

In this work we report new measurements of the total cross sections of the tungsten isotopes ^{182,184,186}W in the energy range 5–560 MeV. We show that both a simple Ramsauer model and a standard spherical global optical potential fail to reproduce the observed differences of cross sections among these isotopes. The essential problem is that the effects of change of radius and change in the isospin terms nearly cancel, leading to a rather weak energy dependence for the cross section differences, whereas the measurements show distinct oscillations in the range 5–100 MeV.

Hartree-Fock calculations describe neutron and proton density distributions separately, and they predict larger r.m.s. radii for neutrons than for protons in heavy nuclei. Thus they may provide the additional physical ingredients required to address the experimental data. We have used such density distributions from a Hartree-Fock-Bogoliubov calculation[11,12)] in microscopic folding models. We have performed both spherical and coupled-channel calculations using this treatment. These calculations adequately describe the observed total cross section differences.

We conclude that understanding total cross section differences between nearby nuclei requires careful attention to details of the nuclear density distributions. Simple models that do not take these details into account may fail, as in the case presented here. We have shown that a folding model based on realistic nuclear densities provides the necessary ingredients for addressing total cross section differences.

II. Experiment

The neutron total cross sections of ^{182,184,186}W in the energy range 5–500 MeV were measured at LANSCE/WNR as part of an extensive survey of total cross sections spanning the periodic table from A=1 to 238.[1)] The measurements were made by the transmission method in which a well-collimated neutron beam is incident along the sample axis and the count rates in plastic-scintillator counters downstream of the samples were compared with the samples in and out of the beam. The data in the main part of the experiment were reported in 1% wide energy bins, with a statistical accuracy of 1% or better in each bin. To adequately exhibit the cross section differences among the separated tungsten isotopes, we have binned the data in 8% wide intervals, with a statistical accuracy of approximately 0.2% in each bin.

The cross section difference data are presented as the ratio of the measured difference to the average of the individual cross sections; *i.e.* as $R_{i-j} = 2\,\sigma_{i-j}^{diff}/(\sigma_i + \sigma_j)$. This has the advantage that the systematic error due to the densities takes a very simple form. For $R \ll 1$, a condition that is well satisfied

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for these measurements,

$$R_{i-j} = 2\frac{\sigma_{i-j}^{diff}}{\sigma_i + \sigma_j} \pm 2\frac{\Delta\sigma_{i-j}^{diff}}{\sigma_i + \sigma_j} \pm \frac{\Delta(nl)_i}{(nl)_i} \pm \frac{\Delta(nl)_j}{(nl)_j}. \quad (1)$$

In this expression, $\Delta\sigma_{i-j}^{diff}$ is the statistical uncertainty in the direct measurement of the cross section difference. The statistical uncertainty in R, represented by the second term, is shown explicitly in the figures. The last two terms are the fractional uncertainties in the areal densities of the two samples. They correspond to a shift in the vertical scale in the figures, but are not shown explicitly. Because these terms may be as large as 0.02, we allow the theoretical calculations to be shifted by an amount that does not exceed this value, and we indicate the size of the shift.

III. Ramsauer and Conventional Optical Models

The nuclear Ramsauer model[13,14] utilizes the assumption that neutron total cross sections can be modeled in terms of the interference between waves which pass through the nucleus and those which go around it. Application of the Ramsauer model to total neutron cross sections[1,15] has resulted in rather good characterizations of their behavior with mass and energy.[2-4] These analyses showed that a fit to better than 3% could be obtained over a wide range of mass and energy. Intput to this simple model contains information on both the nuclear radius and the nuclear asymmetry (*i.e.* $N - Z$), and is therefore useful for gaining insight into the behavior of the cross section differences among neighboring nuclei. However, as shown in Fig. 1, results for the cross section differences are in strong disagreement with the experimental data. The calculations assumed that the nuclear radius varies as $A^{1/3}$ and a typical value for the ratio U_1/U_0 of 0.5 for the real potential. The reason for this very poor agreement has been traced to a cancellation between the effects of increasing the radius and the change in the potential as $N - Z$ increases.

These insights are corroborated by calculations employing a spherical optical model, as shown in Fig. 2. These calculations are based on a standard global parameterization, the "Global A" set from the work of Rapaport, Kulkarni, and Finlay.[16] In this figure, the solid curve, calculated with the unaltered "Global A" potential, yields a very poor reproduction of the experimental data. Assuming that the symmetry terms in the optical potential are fixed at their values for ^{184}W results in oscillations that resemble the experimental behavior, as shown by the dashed line, even though this assumption is incorrect. On the other hand, using constant radii (taken from the values for ^{184}W) in all of the calculations yields a result that is large and opposite in phase from that with constant symmetry terms, as shown by the dotted curve.

We have also performed calculations of the cross section differences with a phenomenological dispersive coupled–channel optical model. This calculation, in which the symmetry terms were held constant, is similar in its general behavior to that shown by the spherical calculation in Fig. 2 with fixed symmetry terms. These results wil be shown in a more complete publication.

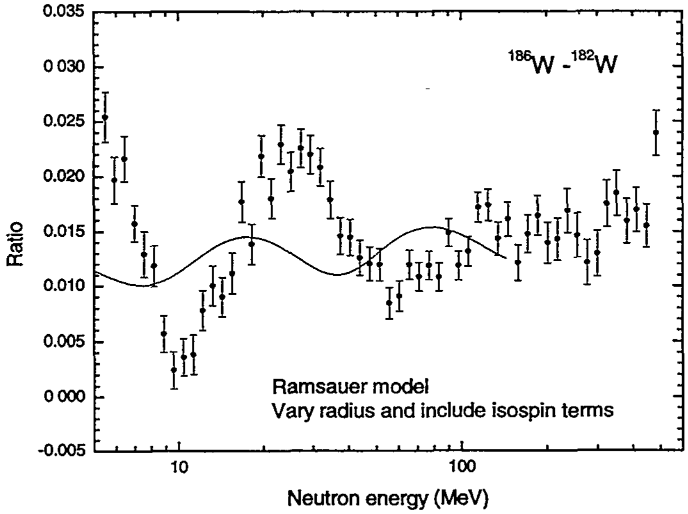

Fig. 1 Comparison of the Ramsauer model with experimental data. The model calculations assume a nuclear radius proportional to $A^{1/3}$ and an isovector / isoscalar ratio of 0.5 for the real potential.

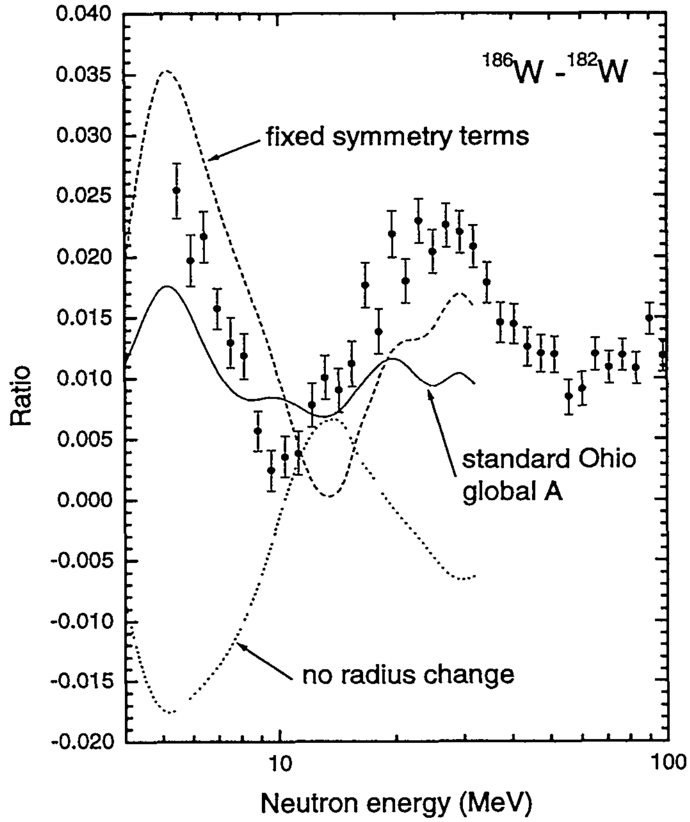

Fig. 2 Comparison of spherical optical model calculations with experimental data. Solid curve: "global potential A" from Rapaport *et al.*[16]; dashed curve: calculations holding symmetry terms fixed at their values for ^{184}W; dotted curve: calculations with all radii fixed at their values for ^{184}W.

IV. Folding Models

The results shown above indicate that a more detailed approach to the physics than provided by simple global optical model parameterizations is required. To do this, we have calculated the total cross section differences among the W isotopes in the energy range 5–200 MeV using a deformed, semimicroscopic optical model potential obtained by folding an effective interaction derived from a nuclear-matter optical potential that is energy and density dependent with deformed nuclear densities. This potential is a coupled-channel extension of a recently developed spherical, Lane-consistent semimicroscopic optical potential,[6] which is based on the work of Jeukenne, Lejeune and Mahaux (JLM) who calculated the optical potential in nuclear matter using a G-matrix formalism.[17,18] We have supplemented these calculations by carrying out folding model calculations in the range 100–500 MeV using an empirical effective interaction devised by Kelly and collaborators.[19] The two sets of calculations allow the entire energy range where the total cross section differences have been measured to be compared with calculations based on a detailed description of the neutron and proton density distributions.

The deformed density distributions used in the present work were calculated in the axially symmetric Hartree-Fock-Bogoliubov framework using the Gogny D1S interaction.[11,12] The rms radius of the neutron distribution is well characterized by $0.926A^{0.34}$, and that for the protons by $2.088A^{0.18}$. The significant deviation of the A-dependence of the proton density from the $A^{1/3}$ behavior assumed in global phenomenological potentials may explain the success of the calculations described here. We also note that the rms radius of the neutrons extends beyond that for the protons (5.452 fm and 5.339 fm for neutrons and protons in ^{184}W, respectively).

Using the same densities, we have also performed calculations in the 100–500 MeV range using the empirical effective interaction (EEI) developed by Kelly and collaborators.[19] This interaction, originally developed at six discrete energies in the 135–650 MeV range, was interpolated in energy and used successfully to interpret neutron total cross section data as well as proton reaction cross section data.[1]

The results are shown in Fig. 3. These calculations yield a quite reasonable reproduction of the W isotope total cross section differences, as shown by the solid curves in the figure. The general behavior of both the amplitude and the phase of the energy variations is rather well reproduced by the calculations. This is a significant improvement over the models described earlier that do not utilize a realistic description of the variation in neutron and proton densities over the isotopic chain. The calculated amplitude of the energy variations in the cross section differences is slightly lower than observed experimentally. This feature of the cross section differences is very probably associated with the fact that the oscillations in neutron total cross sections are somewhat underpredicted by JLM calculations in heavy nuclei. The short dashed curves represent a spherical optical model calculation using the JLM prescription. The EEI calculations are represented by the long dashed curves, and are in good agreement with the JLM in the region of overlap between 100 and 200 MeV.

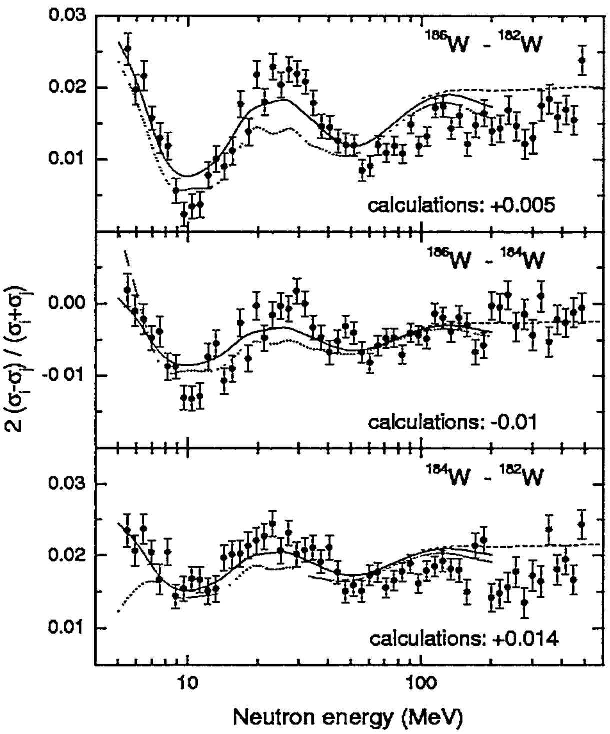

Fig. 3 Comparison between folding optical model calculations based on HFB densities and measured W total cross section differences. The solid curves are JLM coupled-channel calculations, and the short dashed curves are corresponding spherical calculations. The long dashed curves above 100 MeV are EEI calculations. The calculations are shifted by the specified amounts, which are smaller that the uncertainties associated with sample densities.

V. Conclusions and Acknowledgments

The total cross sections of the tungsten isotopes are perplexing. Whereas other isotopic data, such as ^{142}Ce–^{142}Ce can be more easily fit with spherical optical model calculations that include reasonable strengths for the isospin potential, the tungsten data are not amenable to such simple calculations. We have demonstrated this using the simple Ramsauer model. We have shown that conventional optical models yield essentially the same results as the Ramsauer model when isospin is properly incorporated and thus cannot explain the measured isotopic differences. We have also shown that a folding model based on Hartree-Fock wave functions, when used with a Lane-consistent effective interaction, can reasonably accurately fit the results of the measurements.

In summary, we have shown that although standard phenomenological optical models are capable of predicting neutron total cross sections at the few percent level, the more complicated folding model is required to achieve a detailed explanation of total cross section differences among neighboring nuclei. This result is a consequence of the realistic treatment of the separate proton and neutron densities that is possible in such a model.

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